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UCRL-SR-220853

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April 25, 2006

Auspices Statement

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Laser plasma instability reduction by coherence disruption

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Abstract

The saturation levels of stimulated scattering of intense laser light in plasmas and techniques to reduce these levels are of great interest. A simple model is used to highlight the dependence of the reflectivity on the coherence length for the density fluctuations producing the scattering. Sometimes the coherence lengths can be determined nonlinearly. For NIF hohlraum plasmas, a reduction in the coherence lengths might be engineered in several ways. Finally, electron trapping in ion sound waves is briefly examined as a potentially important effect for the saturation of stimulated Brillouin scattering.

Introduction

There is a great deal of interest in understanding the saturation levels of stimulated Raman and Brillouin scattering (SRS and SBS) and in finding techniques to reduce these levels. Much work has focused on delineating the saturation level of the density fluctuation associated with the scattering. For example, in some ideal models used in the code pF3D[1], this density fluctuation is simply saturated at the value at which the ion acoustic or electron plasma wave begins to excite secondary instabilities. To gain further insight into the scattering levels and their control, we briefly discuss a simple model for the SBS reflectivity in the nonlinear state. This model emphasizes that the reflectivity depends on both the level of the density fluctuation and on the coherence length. Hence the reflectivity can be significantly reduced by a reduction of the coherence length. The coherence can be disrupted by nonlinear effects, and an example will be given. More generally, it may be possible to engineer a disruption of the coherence in various ways, as will be discussed. Finally we briefly discuss electron trapping in ion acoustic waves as a potential explanation for the rather low saturated ion wave levels often inferred[2] from observations of SBS.

A simple model for the SBS reflectivity

An ideal model for the reflectivity due to SBS is illustrative. Consider a plasma with a uniform density n and length L, and let the density fluctuation associated with SBS backscatter have a saturated value δn. It is straight-forward to solve the coupled equations for the reflected and incident light waves. The reflectivity r is

$$r = \tanh^2(A), \tag{1}$$

where

$$A = \frac{\pi}{2}\frac{n}{n_{cr}}\frac{\delta n}{n}\frac{L}{\lambda_0}. \tag{2}$$

Here n_{cr} is the critical density for the incident laser light with free-space wavelength λ_0. For A<<1,

$$r \cong \frac{\pi^2}{4}\left(\frac{n}{n_{cr}}\right)^2\left(\frac{\delta n}{n}\right)^2\left(\frac{L}{\lambda_0}\right)^2. \tag{3}$$

For Equation 3 it is assumed that the density fluctuation is coherent over the entire plasma length. More generally, the fluctuation is coherent over some smaller distance ℓ_{coh}<<L. Then we use Equation 3 to describe the reflectivity of each region of length ℓ_{coh} and note that there are L/ℓ_{coh} such contributions to the net reflectivity., giving

$$r \cong \frac{\pi^2}{4}\left(\frac{n}{n_{cr}}\right)^2\left(\frac{\delta n}{n}\right)^2\frac{L\ell_{coh}}{\lambda_0^2}. \tag{4}$$

This ideal model emphasizes that the saturated level of δn is important, but so also is the coherence length. We are reminded of another avenue to reduce the reflectivity;i.e., by coherence disruption.

An example of coherence disruption by nonlinear effects

Let's first consider an example in which the coherence is disrupted by an intensity-dependent effect. We consider a light beam which has been smoothed by a random phase plate and so can de described in terms of speckles with a characteristic width of $f\lambda_0$ (f is the f/number of the beam) and a characteristic length of $8f^2\lambda_0$. These speckles have a distribution of intensities. When super-Gaussian distribution functions[3] due to collisional absorption in a high Z plasma become important, the ion wave frequency becomes intensity-dependent[4], as illustrated in Figure 1. Hence the ion wave frequency can vary from speckle to speckle, an effect which can de-correlate the speckles and reduce the coherence length to $8f^2\lambda_0$. These nonlinear frequency shifts are expected to become significant when $Zv_{os}^2/v_e^2 > 1$, where Z is the ion charge state, v_e the electron thermal velocity, and v_{os} the oscillatory velocity in the averaged intensity electric field.

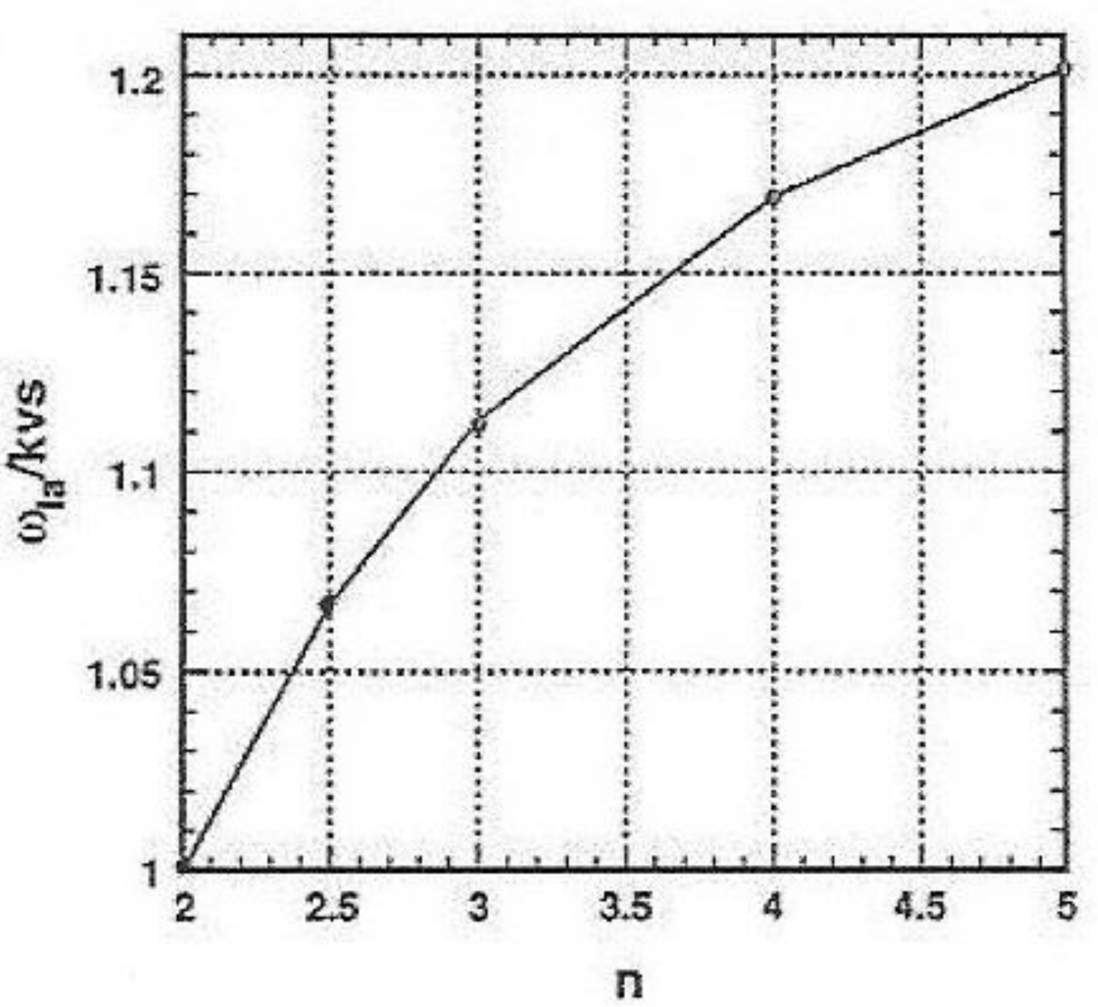

Figure 1: The frequency of an ion sound wave as a function of the index n which varies from n=2 (Maxwellian) to n=5 (super-Gaussian) as Zv_{os}^2/v_e^2 increases. See reference 4.

This reduction in the coherence length is a potential and novel explanation for a surprising reduction of SBS with target Z observed in some recent experiments[5] with the Helen laser. In these experiments, gas bag targets with a variety of gases were irradiated with .53μm laser light, and the SBS back reflection was measured. For targets with CO_2 gas, the ion wave damping has already become rather weak, and significant SBS is observed (a reflectivity of about 10% in these targets with a plasma size of about .5-1mm). However, as the Z of the target plasma was increased, the SBS reflectivity declined. For example, for a gas bag filled with Kr gas, the reflectivity dropped to ≤ 1%!

Coherence disruption via the onset of modified distribution functions is a potential explanation for this surprising behavior. For our estimates, we use the plasma conditions found in Lasnex simulations by L. Suter. We then estimate that $Zv_{os}^2/v_e^2 \sim .3$ for the CO_2 plasma, whereas $Zv_{os}^2/v_e^2 \sim 1.2$ for the Kr plasma. Hence we hypothesize that the speckles become de-correlated in the Kr plasma, and so the coherence length is then reduced to the speckle length. The reflectivity would then be reduced by a factor of about $8f^2\lambda_0/L$. Noting that f=3 for these experiments and taking L~.5mm, we estimate that the reflectivity would decrease to about .5% in the experiments with the Kr plasma. Clearly these estimates are not meant to be quantitative nor to be a unique explanation for these experiments. However, they do help us to think of the saturated state in a richer way and to consider some new possibilities for controlling stimulated scattering.

Application to NIF hohlraum plasmas

The plasmas expected when ignition-scale hohlraums are irradiated with NIF will be hotter (electron temperature ~3-5 keV rather than ~1 keV) and most likely lower Z. Hence $Zv_{os}^2/v_e^2 << 1$, and reduction of the coherence length via modified electron distribution functions is not expected. However, it may very well be possible to engineer a reduction in the coherence lengths in the hohlraum plasma for an ignition target by intentionally modulating the plasma conditions. For example, one might vary the liner material on the hohlraum wall, modulate the composition of a low density foam within the hohlraum , or increase the vorticity of the plasma flow by slightly modifying the hohlraum geometry to enhance the effects of plasmas colliding at an angle. A preliminary hohlraum simulation by P. Amendt has shown that a variation in the composition of the liner on the wall of a hohlraum does lead to a modulation in the conditions of the irradiated plasma. More simulations are needed to explore and optimize this effect.
It is important to note that even a reduction of the coherence length of about 2-3 would be very valuable and that schemes to reduce the coherence length can readily be tested with Omega experiments.

Indeed, instability gain reduction by modulations in the plasma conditions has been observed in a simulation of a gas-filled hohlraum which was irradiated with the Omega laser. In this particular simulation[6] by N. Meezan, the hydrodynamics led to the formation of density modulations, which disrupted the gain for stimulated Raman scattering.. Figure 2 shows a plot of the maximum gain coefficient along a light ray versus the wavelength of the Raman-scattered light. Clearly the modulations in plasma density reduced the integrated SRS gain at any particular wavelength. In this example, the peak gain is estimated to have been reduced by a factor of about 2.

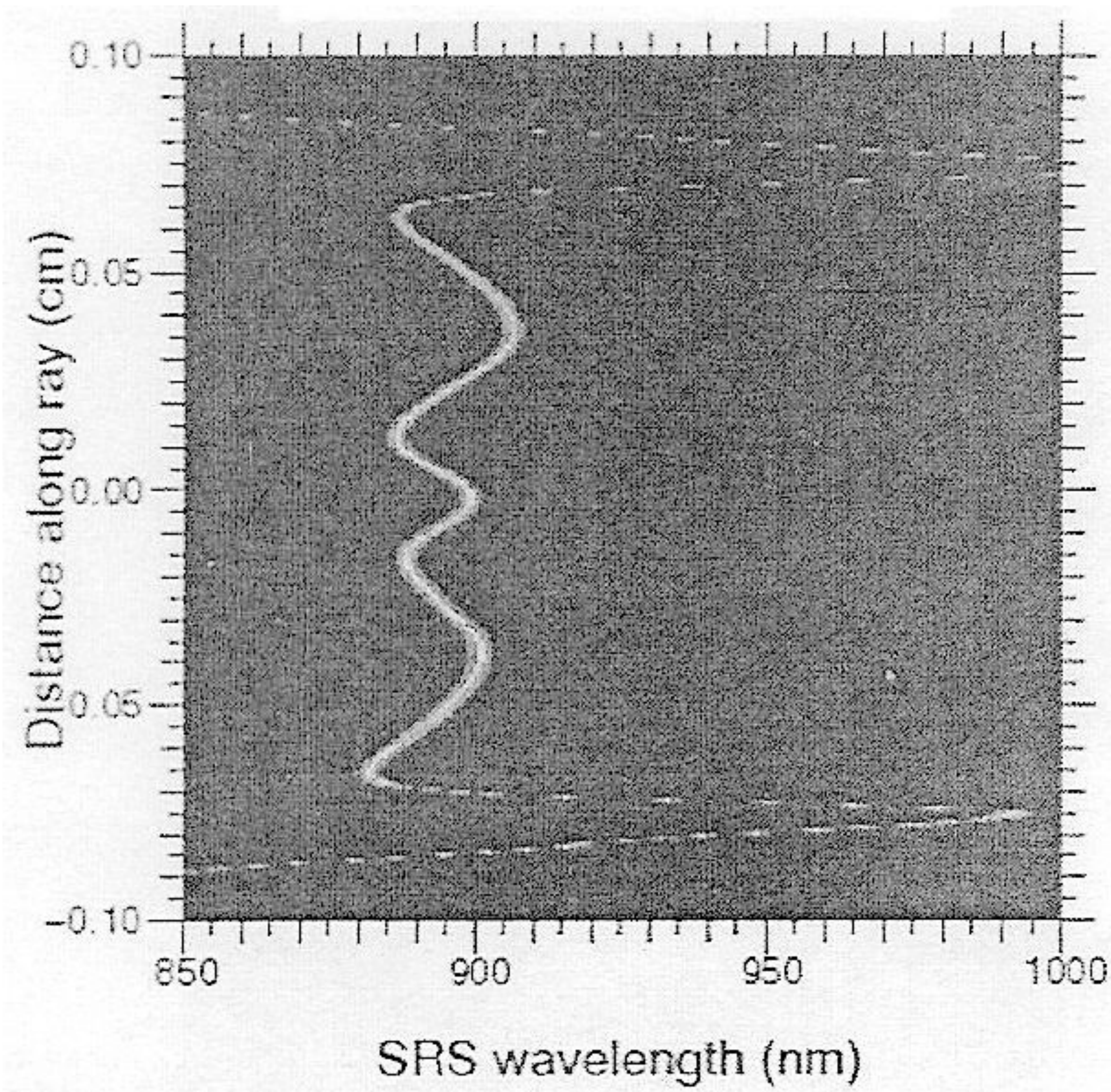

Figure 2: The maximum gain coefficient for SRS along a ray versus the wavelength of the Raman-scattered light.

A simple estimate can be given for the scale length of the modulations in plasma conditions which are needed. We first estimate a scale length L for significant SBS using the gain coefficient for heavily-damped ion waves:

$$Q \cong \frac{\pi}{2} \frac{n}{n_{cr}} \frac{v_{os}^2}{v_e^2} \frac{L}{\lambda_0} / \frac{\nu_i}{\omega_i}, \tag{5}$$

where ν_i (ω_i) is the ion wave energy damping rate (frequency). For typical plasma conditions in a NIF ignition-scale hohlraum, take $(v_{os}/v_e)^2$=.01, n/n_{cr}=.1, ν_i/ω_i-.25, and λo=.35μm. Significant SBS would likely require Q~20-30, which gives L~1.5mm. Hence modulations with a scale length ~500μm could reduce Q by factors of about 3.

A note on electron trapping in ion acoustic waves

Finally, let's conclude with a very brief discussion of electron trapping in ion acoustic waves. This effect could help explain the very low saturated level of ion acoustic waves ofrten inferred from observations of SBS. Electron trapping in ion acoustic waves becomes important at remarkably small amplitudes. The linear theory of Landau damping breaks down when $\omega_{be}>\gamma_{le}$, where γ_{le} is the linear electron Landau damping rate and ω_{be} is the bounce frequency of electrons in the potential trough of the wave. Here $\omega_{be} = \sqrt{ek^2\phi/m} = kv_e\sqrt{\delta n/n}$, since $e\phi/mv_e^2 \cong \delta n/n$. Here k ($\phi$, δn) is the wave number (potential fluctuation, density fluctuation) of the ion acoustic wave, and v_e is again the electron thermal velocity. Hence electron trapping dominates and the slope of the electron distribution function flattens when

$$kv_e\sqrt{\frac{\delta n}{n}} > .005\omega_{i,} \qquad (6)$$

which gives $\delta n/n>10^{-8}$! Perhaps other effects can maintain the slope of the distribution function, such as replenishment of the distribution function by electrons traversing a speckle. The condition for flattening of the slope then becomes $\omega_{be}t_{loss}>1$, where $t_{loss} \sim f\lambda_o/v_e$. Even so, electron trapping effects dominate for quite small amplitudes. For f=8, $\delta n/n>1/2500$! Note also that $\omega_{be}=\omega_i$ when $\delta n/n\sim Zm/M$.

Electron trapping leads to two effects: a frequency shift[7] and a flattening of the slope of the electron distribution function which can cause the Landau damping rate to vanish. This latter effect could be especially important for strongly reducing the damping threshold of the two-ion wave decay instability[8]. For $ZT_e/T_i>>1$, this threshold is determined by the electron Landau damping rate; i.e.,

$$\frac{\delta n}{n} \cong 8\frac{\gamma_{Le}}{\omega_i}. \qquad (7)$$

This secondary instability has been proposed as a saturation mechanism for SBS. One simple model in pF3D simply saturates δn at the damping threshold. We note that a brief overshoot may be needed (as often seen in simulations) to allow the daughter ion waves to flatten the slope of the electron distribution function near the phase velocity in their directions of propagation. We also note that reduction of the Landau damping of electron plasma waves by electron trapping can be important for reducing the saturation levels of SRS by again reducing the damping threshold for the onset of secondary instabilities.

Summary

In summary, we have used a simple model to emphasize that the reflectivity levels of intense laser light in plasmas can be significantly reduced by coherence disruption.

Sometimes, the coherence lengths can be reduced nonlinearly; for example, by modified heated electron distributions in a high Z plasma. For NIF hohlraum plasmas, a reduction in the coherence lengths can be engineered in several ways. Such schemes can be readily tested in future experiments on the Omega laser and might provide a very valuable back-up option for ignition scale experiments on NIF. Finally, electron trapping in ion acoustic waves can have an important effect on the saturation of SBS in laser plasmas.

ACKNOWLEDGEMENTS: This work was performed under the auspices of the U.S. Department of Energy by UC, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

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